

## **Comparison of the Performance of a Conventional and a Modified Plug-Flow Digester for Scraped Dairy Manure**

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*Abstract: This paper presents a comparison of the performance of a conventional and a modified plug-flow digester for scraped dairy cattle manure based on results from 12-month studies to characterize the performance of each design with respect to waste stabilization and biogas production and utilization. Both are full-scale digesters located on commercial dairy farms. The primary objective of this comparison was to determine if either design approach provides superior performance with respect to waste stabilization and biogas production. The modified plug-flow digester was found to provide a higher reduction in total volatile solids (TVS), 39.6 versus 29.7 percent, a higher biogas yield, 3.08 versus 2.21 m<sup>3</sup> per cow-day, and higher electricity production, 13,896 versus 9,380 kJ per cow-day. However, these differences were found to be directly related to the difference in the readily biodegradable fraction of influent TVS, 47 versus 30 percent and were reflected in the rate of electricity generated, 13,896 kJ per cow-day from the modified versus 9,380 kJ per cow-day from the conventional plug-flow digester design. In contrast, specific biogas and methane yields on a kg TVS destroyed basis were essentially the same for both digester designs as was the thermal efficiency of converting biogas to electricity.*

*This comparison suggests that neither design is superior. The observed differences in TVS reduction, biogas yield, and electricity generated appear to be solely a reflection of the difference in the readily biodegradable fraction of influent TVS. This suggests that an estimate of the readily biodegradable fraction of influent TVS is a necessary prerequisite for a reliable prediction of anaerobic digester performance.*

*Keywords: Anaerobic digestion, dairy manure, waste stabilization, pathogen reduction, biogas production and utilization*

### **Introduction**

As a component of dairy manure management systems, anaerobic digestion under controlled conditions has the demonstrated ability to reduce manure related odor problems as well as other potential impacts on air and water quality. In addition, the income generated through the use of the biogas captured as a fuel can at least partially offset the cost of anaerobic digestion and biogas utilization and may add to net farm income. With recognition of these positive attributes by dairy producers, demand for manure biogas systems has increased along with the number of available design options. Thus, livestock producers now face not only the decision of whether or not to incorporate anaerobic digestion with biogas utilization in their waste management systems but also which type of digester to construct. Two of the options available to dairy producers with scraped free-stall housing are conventional unmixed and two-stage, vertically mixed plug-flow digester designs. Unfortunately, the selection of one of these or other available options currently must be based largely on information supplied as part of a marketing effort by the digester supplier, which probably is at least somewhat biased.

This paper presents a comparison of the performance of a conventional and a modified plug-flow digester for scraped dairy cattle manure based on the results from 12-month studies to characterize

performance of each design with respect to waste stabilization and biogas production and utilization. Both performance evaluations were conducted under steady-state conditions. Results from the conventional plug-flow digester performance evaluation have been previously reported by Martin *et al.* (2003).

## Methods and Materials

**Study Sites**—The conventional plug-flow digester evaluated was designed and constructed by RCM Digesters, Inc., Berkeley, California, for AA Dairy, which is located in the southern tier of upstate New York. AA Dairy is a 891 ha (2,200 acre) operation with an average milking herd of 550 Holstein-Friesian cows housed in free-stall barns. Manure is removed from the free-stall barn alleys by scraping into a holding and mixing tank. A piston pump is used to transfer manure daily from this tank to the digester. A screw press is used to remove coarse solids from the digester effluent before the remaining liquid fraction is discharged into a 9,084 m<sup>3</sup> (2.4 million gallon) lined storage pond prior to land application for disposal. Milking center wastewater is discharged directly into this storage pond.

The AA digester dimensions are 34.1 m (112 ft) long by 8.5 m (28 ft) wide by 4.3 m (14 ft) deep, and it has an operating volume of 1,121 m<sup>3</sup> (39,568 ft<sup>3</sup>). The digester has a design hydraulic retention time (HRT) of 24 days, which was based on an anticipated but yet to occur herd expansion to 1,034 cows. The captured biogas is used to fuel a 130 kW engine-generator set. The engine, a Caterpillar 3306, is a diesel engine modified for natural gas and biogas by the addition of spark ignition. Waste heat recovered from the engine-cooling system is used to maintain the digester temperature at approximately 35 °C (95 °F). The digester and engine-generator set have been in operation since 1998.

The modified plug-flow digester evaluated was designed and constructed by GHD, Inc., Chilton, Wisconsin, for Gordondale Farms, which is located in Nelsonville, Wisconsin. Gordondale Farms is a 1,296 ha (3,200 acre) operation with a milking herd housed in free-stall barn that increased from an average of 750 to 860 cows at the mid-point of the performance evaluation. Manure is scraped from free-stall barn alleys into a sump. From this sump, the accumulated manure flows by a combination of gravity and fluming with milking center wastewater to an influent holding tank containing a chopper type pump. The manure accumulated in this tank is mixed and transferred into the digester several times daily with this pump. After coarse solids removal from the digester effluent using a screw press, the remaining liquid fraction is discharged to a holding tank for short-term storage followed by land application for disposal.

The Gordondale Farms digester dimensions are 27.7 m (91 ft) long by 19.0 m (62.3 ft) wide with an operating depth of 3.8 m (12.5 ft) and has an estimated operating volume is 2,007 m<sup>3</sup> (70,866 ft<sup>3</sup>). Unlike a conventional plug-flow digester, the influent chamber of the Gordondale Farms digester is separated into two compartments to allow, at least theoretically, acidogenesis to occur separately from methane formation. Hence, the designer uses the term 'two-stage' to describe the digester. In addition, the digester has two parallel channels connected at one end resulting in a U shaped flow pattern. Thus, the influent enters and the effluent exits at adjacent locations at one end of the digester. Finally, the contents of the Gordondale digester are continually mixed vertically using compressed biogas. The design HRT for this digester, which was based on the assumption of a 750 head Holstein-Friesian milking herd, was 22 days.

The captured biogas is used to fuel a 150 kW engine-generator set rated at 140 kW with biogas. The engine, a Caterpillar 3406, again is a diesel engine modified by the addition of spark ignition to use natural gas and biogas as fuels. Both cooling system and exhaust system waste heat is used to maintain the digester temperature at approximately 35 °C and for milking center water and space heating. The digester and engine-generator set have been in operation since 2002.

**Data Collection**—The basis for characterizing the performance of each digester is a set of materials balances developed from mean influent and effluent concentrations of the physical and chemical parameters identified below in combination with mass flow estimates. For each digester, influent and effluent samples were collected semi-monthly for a period of 12 months; late May 2001 through early June 2002 at AA Dairy and January through December 2004 at Gordondale Farms. Each digester influent and effluent sample was a composite of a series of sub-samples collected over a 15 to 20 minute period of flow to insure that the samples analyzed were representative.

The piston pump used to transfer manure from a holding and mixing tank to the digester at AA Dairy allowed the estimate of the average daily mass flow of manure through the digester based on the number of

strokes per day and the volume of manure displaced per stroke per the manufacturer's specifications. A mechanical counter was used to record the number of piston strokes per day. At Gordondale Farms, the operation of the chopper type pump used to transfer manure from the influent holding tank to the digester was controlled automatically by float switches. This enabled estimate of average daily manure mass flow based on the determination of the volume of manure transferred during each pump operating cycle and recording the number of pump operating cycles per day automatically.

During each sampling episode, the measured volume of biogas utilized, electricity generated, and the hours of engine-generator operation since the last sampling episode were recorded. A Roots specialty service meter was used to measure biogas utilized at AA Dairy and initially at Gordondale Farms. However, the owners of Gordondale Farms suspected that the Roots gas meter was restricting biogas flow to the engine-generator set and thus the amount of electricity generated. The replacement of this meter with a non-flow restricting FCI FlexMASSter thermal mass flow meter revealed that the Roots meter was accurately measuring and not restricting biogas flow. Utility type kilowatt-hour meters were used to measure and record electricity generated at both farms.

**Sample Analyses**—All digester influent and effluent samples collected were analyzed to estimate concentrations of the following parameters: total solids (TS), total volatile solids (TVS), chemical oxygen demand (COD), soluble chemical oxygen demand (SCOD), total volatile acids (TVA), total Kjeldahl nitrogen (TKN), ammonia nitrogen ( $\text{NH}_4\text{-N}$ ), total phosphorus (TP), and pH. U.S. Environmental Protection Agency (1983) methods were used for TS, TVS, TKN, TP, and pH determinations. American Public Health Association (1995) methods were used to determine COD, SCOD,  $\text{NH}_4\text{-N}$ , and TVA concentrations.

At both farms, each digester influent and effluent sample also was analyzed to estimate the density of the fecal coliform group of indicator organisms (fecal coliforms). In addition, each AA Dairy digester influent and effluent sample was analyzed to estimate the density of the pathogen, *Mycobacterium avium paratuberculosis*. Each Gordondale digester sample also was analyzed to determine the density of a second group of indicator organisms, fecal streptococci. Densities of both groups of indicator organisms were estimated using the multiple tube fermentation technique (American Public Health Association, 1995). The densities of *M. avium paratuberculosis*, which is responsible for Johne's disease in dairy cattle and other ruminants (Merck, Inc., 1998), were determined using the "Cornell Method," which has been described by Stabel (1997). Although Stabel reported the Cornell Method to be less sensitive than other methods, it satisfies the requirements of the USDA National Veterinary Services laboratory proficiency-testing program.

The methane and carbon dioxide content of AA Dairy biogas was estimated by gas chromatography using ASTM Method D1946 (ASTM, 1990). Hydrogen sulfide and ammonia concentrations respectively were estimated using EPA Method 16 and Sensidyne ammonia detector tubes. The methane and carbon dioxide content of the Gordondale Farms biogas was determined using a CES-Landtec Gem™ 500 Landfill Gas Monitor. Hydrogen sulfide and ammonia concentrations were estimated respectively using ASTM Method D5504-01 (ASTM, 2001) and EPA Method 350.1.

Batch studies were conducted to estimate the readily biodegradable and refractory fractions of TVS in random samples of the AA Dairy and Gordondale Farms digester influents. These studies were laboratory scale studies in which two liters of manure was maintained at 35 °C (95 °F) in glass reactors. Water traps were used to vent the biogas produced and maintain anaerobic conditions. Each reactor was mixed daily and sampled to determine TVS concentrations on days 0, 15, 20, 30, 45, and 55.

**Data Analysis**—Each data set generated was analyzed statistically for the possible presence of extreme observations or outliers using Dixon's criteria for testing extreme observations in a single sample (Snedecor and Cochran, 1980). If the probability of the occurrence of a suspect observation, based on order statistics, was less than five percent ( $P < 0.05$ ), the suspect observation was considered an outlier and not included in subsequent statistical analyses. The Student's *t* test was used in two-way comparisons to determine the statistical significance of the difference between means. To equalize variances, densities of fecal coliforms, fecal streptococci, and *M. avium paratuberculosis* were transformed logarithmically ( $\log_{10} (Y+1)$ ) prior to statistical analysis to determine if differences in influent and effluent densities were statistically significant.

The determinations of the readily biodegradable and refractory fractions of TVS from the results of the batch studies were based on the assumption that as solids retention time (SRT) approaches infinity, the

readily biodegradable fraction of TVS is completely destroyed. Thus, the refractory fractions of TVS were determined graphically by plotting a time-series of ratios of TVS concentrations to the initial TVS concentration versus the inverse products of the initial TVS concentration and the corresponding unit of time. Then, the ordinate axis intercepts, which represent the TVS remaining as time approaches infinity, were determined using liner regression analysis.

## Results and Discussion

**Waste Characteristics**—As shown in Table 1, the volume of digester influent per cow-day at Gordondale Farms was significantly higher than that at AA Dairy. This difference is at least partially a reflection of the inclusion of milking center wastewater in the Gordondale Farms digester influent. As noted above, the milking center wastewater at AA Dairy is discharged directly into the digester effluent storage facility. If it assumed that the USDA (1992) standard reference value for the rate of manure excretion by dairy cattle, 0.052 m<sup>3</sup> (1.82 ft<sup>3</sup>) per 635 kg (1,400 lb) cow-day, is a reasonable estimate for Gordondale Farms, it appears that the rate of process water (milking center wastewater, spillage from drinkers, and other water used for cleaning) is approximately 0.034 m<sup>3</sup> (9 gal) per cow-day, which is a reasonable value.

**Table 1. Comparison of AA Dairy and Gordondale Farms waste characteristics.**

Parameter	AA Dairy	Gordondale Farms
Volume, m <sup>3</sup> /cow-day	0.059	0.086
Total solids, kg/cow-day	6.7	7.6
Total volatile solids, kg/cow-day	5.7	5.8
Fixed solids, kg/cow-day	1.0	1.8
Chemical oxygen demand, kg/cow-day	9.1	6.0
Total Kjeldahl nitrogen, kg/cow-day	0.28	0.30
Total phosphorus, kg/cow-day	0.048	0.067

Gordondale Farms liberal use of composted coarse solids separated from the digester effluent for bedding probably is responsible the higher TS, FS, and TP digester loading rates shown in Table 1. The average FS content of these separated solids is 31 percent, which is approximately double the USDA value of 15.6 percent for typical dairy cattle manure. In addition, these separated solids contain almost 38 percent of the TP in the digester effluent before separation.

Although the mass of TVS per cow-day entering the AA Dairy and Gordondale Farms digesters was essentially the same, the readily biodegradable fractions differed substantially. The results from the batch biodegradability studies described earlier indicated that 47 percent of the Gordondale Farms digester influent TVS were readily biodegradable versus only 30 percent for the AA Dairy digester influent TVS. This difference probably is a reflection of differences in ration roughage content.

**Digester Operation**—The design and operating parameters for the AA Dairy and Gordondale Farms digesters are summarized and compared in Table 2. As noted earlier, the AA Dairy digester was designed for a herd of 1,034 lactating cows in anticipation of a future herd expansion that has yet to occur. Thus, the actual HRT also was longer than the design value of 24 days but would be reduced to 18 days if a herd expansion to 1,034 cows did occur. The actual HRT of the Gordondale Farms digester at the design herd size of 750 cows also was substantially longer than the design value of 22 days and only decreased marginally with the addition of 110 cows. The decrease, from approximately 31 to 28 days, was moderated by a slight decrease per cow-day in estimated process wastewater generation.

**Table 2. Comparison of AA Dairy and Gordondale Farms digester operating parameters.**

Parameter	AA Dairy	Gordondale Farms
Herd size, lactating cows	550	750-860 <sup>A</sup>
Actual hydraulic retention time, days	34	29 <sup>B</sup>

<sup>A</sup>Herd size increased from 750 to 860 cows at the beginning of the seventh month of the study.

<sup>B</sup>Average value over 12 months.

**Waste Stabilization**—Table 3 provides a comparison of the performance of AA Dairy and Gordondale Farms anaerobic digesters with respect to waste stabilization based on differences between mean influent and effluent concentrations. As indicated, there are similarities and differences. For example, the observed reductions in COD and TVA concentrations were essentially the same whereas the Gordondale Farms digester produced substantially higher reductions in the concentrations of TS, TVS, and SCOD. The difference in the reduction of TVS, and by extension, TS concentrations is consistent with the estimates the readily biodegradable TVS fractions from the batch biodegradability studies. However, the lack of

correlation between TVS and COD reductions has no apparently logical explanation. The work of Morris *et al.* (1977) suggests that TVS and COD reductions during the anaerobic digestion of dairy cattle manure should be of essentially equal magnitudes as was observed at Gordondale Farms. For a bench-scale semi-continuous flow digester with an HRT of 30 days, Morris *et al.* reported TVS and COD reductions of 37.6 and 40.6 percent, respectively. This suggests that the COD reduction for AA Dairy may be an overestimate.

**Table 3. Comparison of the performance of the AA Dairy and the Gordondale Farms digesters with respect to waste stabilization and indicator organisms and pathogen density reductions based on differences between mean influent and effluent concentrations.**

Reductions	AA Dairy	Gordondale Farms
Total solids, %	25.1	35.4
Total volatile solids, %	29.7	39.6
Fixed solids, %	— <sup>A</sup>	31.1
Chemical oxygen demand, %	41.9	38.5
Soluble chemical oxygen demand, %	30.0	58.8
Total volatile acids, %	86.1	87.8
Total Kjeldahl nitrogen, %	— <sup>A</sup>	— <sup>A</sup>
Total phosphorus, %	— <sup>A</sup>	— <sup>A</sup>
Fecal coliforms, log <sub>10</sub>	2.8	2.3
Fecal streptococcus, log <sub>10</sub>	No data	1.3
<i>M. avium paratuberculosis</i> , log <sub>10</sub>	2.1	No data

<sup>A</sup>The observed difference between influent and effluent concentrations was not statistically significant (P<0.01).

The lack of statistically significant differences (P<0.01) between influent and effluent concentrations of TP and TKN suggests that both digesters were operating in an ideal plug-flow mode with no accumulation of settled solids. However, the mean reduction in FS concentration for the Gordondale Farms digester suggests otherwise. The reason for this apparent contradiction is unclear. One possible explanation is that the FS apparently accumulating in this digester are comprised primarily of soil from the unpaved free-stalls. The lack of a statistically significant difference between influent and effluent TKN concentrations for both digesters indicates that any nitrogen loss through NH<sub>4</sub>-N desorption during the digestion process is negligible.

As also shown in Table 3, both digesters provided greater than two log<sub>10</sub> (99 percent) reductions in the density of the fecal coliform group of indicator organisms. In addition, the AA Dairy digester produced a similar but somewhat lower reduction in the density of the pathogen, *M. avium paratuberculosis*, and the Gordondale Farms digester provided more than a one log<sub>10</sub> (90 percent) reduction in fecal streptococcus density. Unfortunately, adequate resources were not available to determine reduction during anaerobic digestion of the density of fecal streptococcus at AA Dairy or *M. avium paratuberculosis* at Gordondale Farms.

**Biogas Production and Composition**—As shown in Table 4, there was a substantial difference in the rates of both biogas and methane production from the AA Dairy and Gordondale Farms anaerobic digesters on both a per cow-day and a per kg TVS added basis. These differences are reflections of the difference in the readily biodegradable fractions of influent TVS. However, there is little difference in both specific biogas and specific methane yields per kg TVS destroyed. The specific biogas yields on a m<sup>3</sup> per kg TVS destroyed for both digesters are somewhat higher than the maximum typical value for wastewater treatment biosolids of 1.12 m<sup>3</sup> per kg TVS destroyed (Metcalf and Eddy, Inc., 2003).

**Table 4. Comparison of rates of biogas and methane production and specific yields from the AA Dairy and Gordondale Farms plug-flow anaerobic digesters.**

		AA Dairy	Gordondale farms
Rate of production, m <sup>3</sup> /cow-day	Biogas	2.21	3.08
	Methane	1.30	1.72
Specific biogas yields	m <sup>3</sup> /kg TVS added	0.39	0.56
	m <sup>3</sup> /kg TVS destroyed	1.30	1.36

Specific methane yield	m <sup>3</sup> /kg TVS added	0.23	0.30
	m <sup>3</sup> /kg TVS destroyed	0.77	0.76
	m <sup>3</sup> /kg COD destroyed	0.34	0.74

As also shown in Table 4, there was a substantial difference between the AA Dairy and Gordondale Farms digesters on a specific methane yield on a m<sup>3</sup> per kg COD destroyed basis. Theoretically, the destruction of one kg of ultimate biochemical oxygen demand (BOD<sub>u</sub>) should result in the generation of 0.35 m<sup>3</sup> of methane (5.62 ft<sup>3</sup> per lb) under standard conditions (0 °C, 1 atm) (Metcalf and Eddy, Inc., 2003). Although not all COD is readily biodegradable, it can be assumed that COD reduction is equal to the reduction in BOD<sub>u</sub>. Therefore, the observed specific methane yield on a COD destroyed basis for the AA Dairy digester suggests that the observed COD reduction (Table 3) is not an overestimate as previously hypothesized. Conversely, the COD destroyed specific methane yield for the Gordondale Farms digester suggests that the observed COD reduction for this digester is an overestimate. Currently, there is no obvious explanation for this apparent dilemma.

As shown in Table 5, the methane content of the Gordondale Farms biogas was somewhat lower than that in the AA biogas, but both were within the expected range of values for dairy cattle manure. The difference in biogas hydrogen sulfide content is consistent with the previously stated assumption that AA Dairy was probably feeding a higher roughage ration. In the AA Dairy and Gordondale Farms biogas samples analyzed, ammonia was only present in trace amounts indicating that ammonia should not be a significant source of oxides of nitrogen (NO<sub>x</sub>) formed during biogas combustion.

**Table 5. Comparison of AA Dairy and Gordondale Farms biogas composition**

% by Volume	AA Dairy	Gordondale Farms
Methane	59.1	55.9
Carbon dioxide	39.2	43.8
Hydrogen sulfide	0.193	0.310

**Biogas Utilization**—During the performance evaluation of the AA Dairy anaerobic digester, an average of 5,158,800 kJ (1,433 kWh) of electricity was generated daily, which translates into 9,380 kJ (2.6 kWh) per cow-day. After a problem with the Gordondale Farms engine-generator set was resolved, an average of 11,950,560 kJ (3,320 kWh) of electricity was generated daily or 13,896 kJ (3.9 kWh) per cow-day, which is slightly higher than the design estimate of 13,320 kJ (3.7 kWh) per cow-day. The difference between farms on a cow-day basis reflects the previously discussed difference in TVS reduction during digestion and the resulting difference in biogas yields.

At AA Dairy, an average of 4,231,780 kJ of electricity was generated per 1,000 m<sup>3</sup> (33.29±1.13 kWh per 1,000 ft<sup>3</sup>) of biogas utilized, which translates into a thermal conversion efficiency (biogas to electricity) of approximately 20 percent. At the slightly higher thermal conversion efficiency of about 21 percent, Gordondale farms generated 4,511,688 kJ of electricity per 1,000 m<sup>3</sup> of biogas utilized (35.49 kWh per 1,000 ft<sup>3</sup>). It is noteworthy that neither engine-generator set approached the thermal conversion efficiency of 30 percent suggested to be feasible for biogas fueled internal combustion engines (Koelsch and Walker, 1981).

## Conclusions

From this comparison of results from the evaluations of a conventional and a modified plug-flow digester for scraped dairy cattle manure, it appears reasonable to conclude that neither design is superior based on the results from 12-month studies to characterize performance of each design with respect to waste stabilization and biogas production and utilization. The differences in TVS reduction, biogas yield, and electricity generated observed appear to be solely a reflection of the difference in the readily biodegradable fraction of influent TVS. This suggests that an estimate of the readily biodegradable fraction of influent TVS is a necessary prerequisite for a reliable prediction of performance.

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